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Structural Characterization of Traditional Moment-Resisting Timber Joinery

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Abstract
This paper investigates the structural performance of traditional moment-resisting interlocking timber joints for modern building construction. Gradually improved over generations, traditional Japanese and Chinese interlocking connections have proven structural integrity. In this paper, first, an overview of the development of historical Japanese and Chinese joinery techniques is presented. Second, state-of-the-art numerical modeling techniques for solid contact-only timber connections are reviewed. A hypothetical case study is then used to contextualize a selection of four interlocking joints in a modern building structure. The structural behavior of these joints is analyzed by means of finite-elements considering material failure and geometric nonlinearity. The structural capacity and the rotational stiffness of the joints are investigated. The goal of this research is to initiate a classification of interlocking joint typologies based on their structural behavior.

Keywords: moment-resisting, interlocking joints, wood, traditional technology, finite element analysis

1. Introduction
Timber construction plays an important role in architectural history, in modern construction methods and in sustainable design, for which wood-only joinery techniques have been used for centuries. Traditional joinery typologies are the product of successive, empirical improvements over generations of artisans [1]. However, over the industrialization era, many traditional wood-only construction techniques were abandoned in favor of more efficient and profitable modern connections with mechanical fasteners [2]. Today, this comes along with the use of engineered materials such as glue-laminated timber. This shift of practice lead to the development of connections with quantifiable capacity but neglecting the intrinsic anisotropic properties of natural timber.

Conversely, in the past, the structural integrity of traditional joinery techniques was proven mainly through in-situ de-facto testing. Today, building codes include little-to-no information about the application of wood-only carpentry connections in comparison to those with mechanical fasteners [2]. However, examples of historic timber buildings with a life span of multiple centuries have demonstrated many advantages of interlocking timber joints in severe loading cases, e.g. in the case of earthquakes in Japan or China [2, 3, 4]. Another potential of contact-only connections is their non-destructive disassembly for reconfiguration allowing for sustainable solutions through their replacement or repair of structural elements [5, 6]. Remarkable examples include the Japanese Ise-Shrines, which are rebuilt in a 20-year frequency for the past 1300 years while reusing or repairing the wood that has not decayed [7]. Additionally, these ancient techniques have the capability of quicker construction through new technologies. Recent developments in digital fabrication make possible custom and automated manufacturing of traditional wood-only connections for new buildings [8].

1.1 Outline

This initial study on interlocking timber joints is part of a larger investigation of how this ancient technology can be used in today's building construction. This form of connection-design is critical in modern construction as wood-only joinery has the potential to achieve increased sustainability by easing recycling, long-term maintenance, disassembly and reassembly. First, through an extensive literature review, a selection of Japanese and Chinese joinery typologies are presented alongside a discussion of their specific use in the building context. Second, the paper investigates the mechanical behavior of these joints with state-of-the-art modeling techniques. The final goal is to translate insight from these findings to classify a library of interlocking joints based on their structural behavior.

1.2 Traditional Chinese timber joinery

China holds a millennial-old tradition in using timber for load-bearing structures, making carpentry the most important building technology and profession. After more than 2000 years of evolution and progression, this culture has formed a complete system of wood construction, which often exhibits complex geometries, and the assembly of numerous wood pieces [4]. This was achieved through the development of complex joinery geometry without the use of iron or steel fasteners. The oldest technical manual on buildings in Chinese literature is the *Yingzao Fashi*, the "Treatise on Architectural Methods" dating back to the year 1103. It reports a unified set of architectural standards for builders and artisans. Several timber joineries have been recorded in hand-drawn illustrations, without specifying dimensions. Since the Song dynasty (960 – 1279), timber joineries have been gradually simplified. In the Qing Dynasty (1644 to 1911), the interlocking connection between columns and beams in wooden frames, as well as the use of dovetail joints, gradually became conventional. During this period, another official regulation, the *Municipal Engineering Practice Rules* was published (1734). *The Construction Technology of Greater Woodwork in the Qing Dynasty* (1985) [9] was one of the first publications to explicitly list the names of ancient timber joineries at that time. Ma Bing Jian, in the book *The Manufacturing of Greater Woodwork in the Qing* (1991) [10], listed and classified the existing ancient wooden joineries into five categories of greater woodworks, reporting a total of 21 types, with illustrations and simple description of mechanical characteristics.

1.3 Traditional Japanese timber joinery

Because of its heavily forested volcanic islands, Japan developed the most advanced techniques of timber construction over millennia [11]. In addition, adaptable and demountable timber systems were preferred in response to natural disasters and a need for constant city relocations. Entire cities made from timber were constructed for disassembly and transported [12]. In cultural and temple buildings of the Endo era (1603 - 1867) in Japan, up to 100 different wood-joint typologies were used [2]. Unique joints were selected based on their geometry and placement in the building. The knowledge for crafting at least 200 - 400 different joints was required before becoming master carpenter [2, 11]. The linear nature of the wood material, combined with continual need for flexibility gave rise to hierarchical modular arrangements of structural components for making post-to-beam frame construction the most common construction system [11, 12]. In the last decades, Japanese firms have developed a highly efficient technological adaptation of age-old carpentry techniques to make industrially pre-cut timber framing the predominant residential construction method today [12].

1.4 Structural analysis and numeric modeling of timber joints

Up to now, a limited number of fundamental studies on the structural behavior of traditional Chinese wood connections exist [4]. In 1992, Wang [13] published *A preliminary study of statics in the traditional wood frame*, which pioneered the field of mechanical analysis on ancient wooden structures in China. Modern building codes in Japan nowadays require the reinforcement of traditional carpentry joints with metal fasteners [12]. Similarly, the European Norm EN 1995 for timber structures does not cover wood-only carpentry joints: only connections with metallic fasteners or adhesives are favored. Only some EU countries maintain standards for carpentry joints in their national appendices to EN 1995, which are often limited to simple step-joints for roof trusses or perpendicular mortise and tenon joints. Equivalently, the Swiss SIA norm only considers step-joints, where the analysis considers primarily the verification of stress limits, without considering the stiffness of the joint.

Because analytical methods are often limited to simplified geometries and basic assumptions on the structural behavior, it is complex to apply these assumptions to geometrically challenging traditional carpentry joinery. Recently, increasing interest in understanding the behavior of wood-only connections has motivated several research studies involving their numerical simulation. Connections in traditional European truss structures have received special attention from researchers. Parisi and Cordié [14] studied traditional Mediterranean and Alpine roof truss joints, aiming to describe the joint behavior as the basis for retrofitting. They developed analytical and finite element (FE) models and compared them to results from experimental tests. The FE analysis was carried out with 2D elements, reducing the joint geometry into one plane. The mortise and tenon system behavior has been investigated with FE models by Koch et al. [15], Descamps et al. [16], and Kekeliak et al. [17]. The simulation of dovetail halved joints for trusses were addressed by Drdácký et al. [18]. Sangree and Schafer [19] focused on the halved and tabled scarf joint and the stop-splayed scarf joints used in American timber truss bridges, identifying their limit states through experimental and FE analysis.

Wood-only connections of historic buildings in Japan, Korea and China are subjected to recent research, some of which includes the development of FE models to assess their mechanical characteristics. Guan et al. [20] studied the traditional beam to column *Nuki* joints in Japanese buildings. Special focus was put on the contact formulations to correctly treat the effect of introduced wedges. Jeong et al. [21, 22] studied traditional wood joints through FE modeling of the Korean *sagae* beam-to-column joint and a beam-to-beam dovetail connection. Instead of traditionally using solid wood, they reproduced the joint with glue-laminated timber. In addition, they conducted experimental tests to validate the FEM results. Chen et al. [23] carried out a comprehensive study on two types of traditional Chinese beam-to-column dovetail mortise-tenon joints that included experimental testing and FE modeling to obtain a trilinear model of the moment-rotation behavior. Li et al. [24] focused on the effect of looseness in historic Chinese dovetail mortise and tenon joint.

The literature on interlocking joints concentrates on the analysis of few different joint typologies. There are limitations in literature in terms of analyzing a variety, or a library of ancient interlocking wood joints to develop an extensive relative comparison between joints. From the review of the state-of-the-art FEM techniques, it could be concluded that the anisotropic mechanical properties of the wood material, the surface contact as well as the overall joint load-deformation behavior, can be appropriately simulated with a careful setup of the numerical model. Eventually, a full FEM campaign could produce relative comparisons within a library of joints.

2. Selection of joints

A case-study building, inspired by a field survey of a newly constructed three-story building in Qiantong (Ninghai County, Zhejiang province, China), with a wooden *through-type* frame structure is used as a reference system for the sizing of the beams and joints. Through-type frames combine columns and girders as well as secondary beams spanning between them [4]. The case study building is constructed on a 3-meter by 4-meter column grid. Girder ends are connected either at columns or run continuously through them. Primary girders span between columns in the short building direction (Figure 1 (a), section 1-1) and secondary beams span between the girders (section 2-2). With a load case of dead and live loads, a uniformly distributed design load of 6.2 kN/m^2 is assumed. For this loading, the beams sections have been dimensioned.

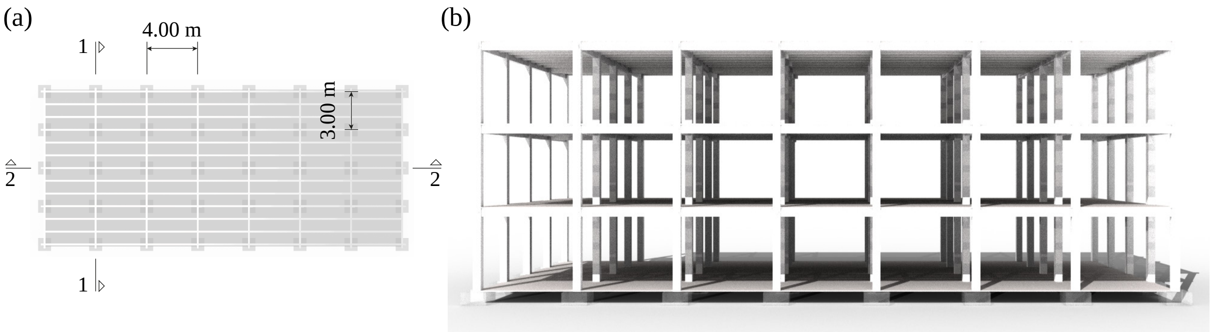

Figure 1. Case study – Primary structural system: (a) ground plan, (b) schematic view

For this case-study building, a selection of Chinese and Japanese through-type joints is shown in the top row of Figure 2. These joints were selected through careful investigation of the literature review and the conclusion that these are commonly used joints in China and Japan in modern construction.

Joint A is situated at the roof level of buildings where beams are inserted into the column from above forming a *bridle joint*. The two beams connected in joint A are halved and form a *cross lap-joint*. Further, two typical Japanese connection details for through-type frames are studied. Figure 2 B shows a *Nuki* joint where a beam is continuously running through the column. Two wedges allow for a continuous contact between the column and the beam and guarantee a rotational stiffness [20]. Joint C connects two beams with a *long tenon* through the column opening. The tensile connection at the beam top permits a rotational stiffness [2]. Joint C is used when building dimensions exceed available beam lengths. In Europe, an equivalent connection topology is completely unknown and would require the use of steel fasteners [2]. However, rounded, CNC-cut versions of such long tenon connection between two beams are commonly used in present building construction in Japan [2, 12]. The *dovetail joint* D describes the common connection of secondary beams to the girders or to a column head [22]. This connection detail is frequently used in Chinese, Japanese and European timber construction.

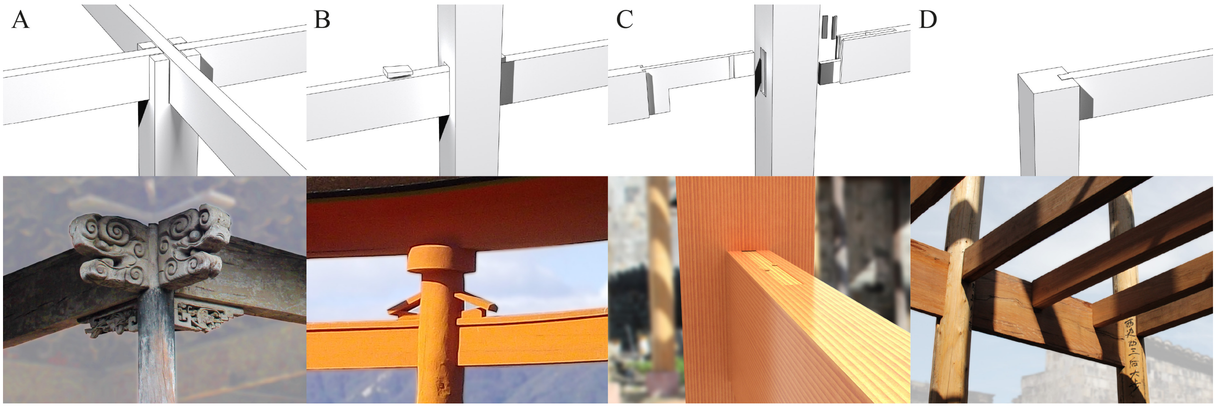

Figure 2. Selection of commonly used Chinese and Japanese joints.
Top row: analyzed joint models; Bottom row: variations of joints in actual building structures.

3. Numerical modelling assumptions

3.1 Material model

Wood is a naturally grown, anisotropic and inhomogeneous material made of longitudinal tubular cells. The material properties highly depend on the orientation of the grain against loading directions, which can have a significant influence on the capacity and stiffness of the joint. For this study, the mechanical model of timber is simplified to a transversely isotropic material that distinguishes strong directional properties parallel to the grain from those of the transverse plane unifying tangential and radial grain directions. Further, the material model considers an elastic-plastic behavior of the wood, as well as material failure, hardening and post peak softening [25]. Douglas fir, being one of the most typical timber materials in North American wood construction, has been selected for the following analyses. The considered mechanical properties listed in Figure 3 (a) are those of grade 1 Douglas fir at 20 °C with a wood moisture content (WMC) of 12 % [25].

3.2 Joint geometry and modeling

As Figure 3 (b) illustrates, typical cross section sizes are used: columns are 12×12 nominal (11.25” by 11.25”, or 285.75 mm by 285.75 mm) and beams are 4×12 (3.5” by 11.25”, or 88.9 mm by 285.75 mm). To remain consistent with traditional joint geometries, dimensions (e.g. tenon widths and lengths, or key sizes) maintain sizing ratios retrieved from field-surveys or reported in literature. The interlocking region of the joints and the beams up to 1.5D away from the column face are modelled with solid finite elements. This considers the main region where stresses are concentrated. The strong direction (grain) of the transversely isotropic material model is aligned parallel to the local x-axis of the solids. To simplify the analysis and to reduce computational complexity, the solid beam portions are coupled to linear beam elements that extend until mid-span, where a symmetry boundary condition is applied (see Figure 3). The interface between all solid joint parts is considered with surface-to-surface contact models (coefficient of friction μ = 0.6).

(a)

E_0	[MPa]	16500
E_{90}	[MPa]	960
G_0	[MPa]	810
G_{90}	[MPa]	350
$f_{t,0}$	[MPa]	57.0
$f_{t,90}$	[MPa]	1.8
$f_{c,0}$	[MPa]	36.9
$f_{c,90}$	[MPa]	7.2
$f_{v,0}$	[MPa]	6.9
$f_{v,90}$	[MPa]	9.7
y	[kg/m^3]	500
WMC		12 %

(b)

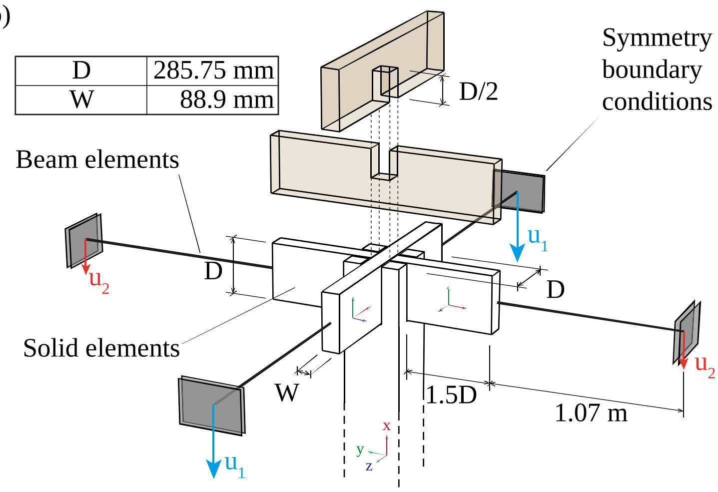

Figure 3. (a) Mechanical properties of Douglas fir, (b) sizing and modeling of the joints, here shown for joint A.

3.3 Loading and analysis

Each joint is analyzed by means of FEM using the commercial software LS Dyna®. A displacement driven, material and geometric non-linear analysis is used to load the joints until failure. The displacement is applied at the beam mid-spans as shown in Figure 3. To simulate the asymmetric loading condition of the building structure, the primary beam-ends are displaced with a higher magnitude (u_1) than the secondary beams (u_2).

4. Results

The goal of the analysis was to extract the relative capacity and stiffness of each joint to understand the behavior of ancient interlocking wood joint techniques. Figure 4 illustrates the principle stress distribution (parallel to grain axis) and the deformed geometries (10x magnified) for joints A and C at different states of incremental loading until failure. Figure 4 (a) to (c) indicates that joint A fails in tension at the top fibers of the section. The analysis showed a brittle failure of joint A through cracking of the whole section (see Figure 4 (c)). In contrary, as illustrated in Figure 4 (d) to (f), joint C fails through an opening of the joint, i.e. the joint pieces disconnect before material failure is reached.

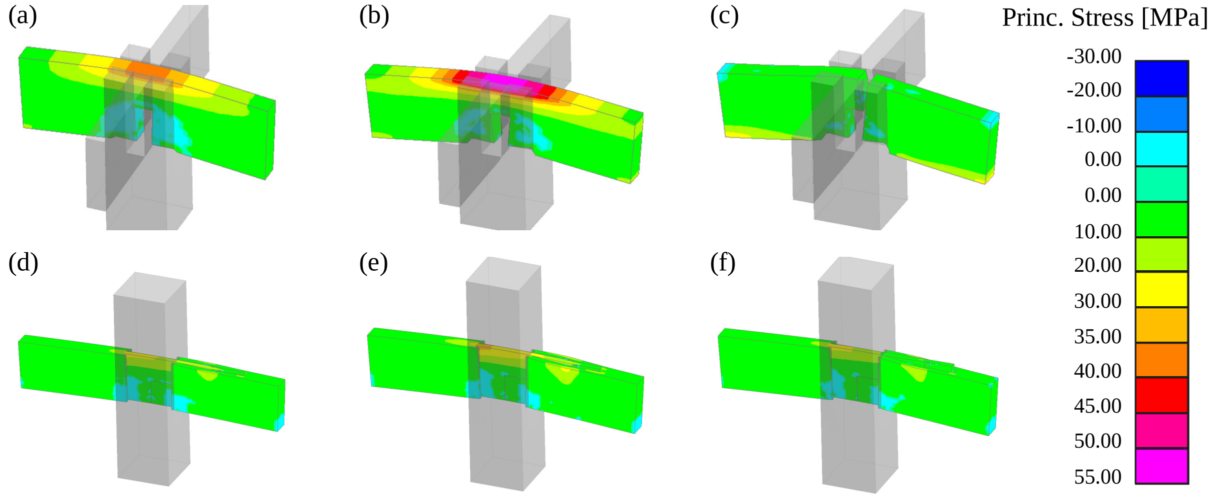

Figure 4. Deformed geometries of joints at different states of loading until failure, and corresponding principal stress distribution states for: (a) to (c) joint A, (d) to (f) joint C.

To compare the capacity and stiffness of all joints, Figure 5 plots the bending moment against the rotation of the primary beams. Moment and rotation are measured in reference to the cross-section of the primary beam at the column face. Joint B shows the stiffest moment-rotation behavior (steepest slope). This is due to the continuity of the beam that runs through the column opening without being weakened. In contrast, joint A has a reduced cross section height due to the halved lap joint. Compression forces are transferred through the secondary beam, perpendicular to its fiber direction, causing a less stiff behavior. The weakening of the cross section of joint A further causes a brittle failure dominating the behavior as shown in Figure 4 (c) and Figure 5. However, both joints, A and B, resist a nearly equivalent ultimate bending moment of 27 kNm. This is approximately the same magnitude as the maximum bending moment in main beams caused by the design load in the case study building.

Joint C reaches an ultimate moment capacity of 15 kNm. At a rotation of 5.0 mrad, joint C opens and exhibits zero stiffness when further rotated. The dovetail joint D shows a limited moment capacity and exhibits big rotations. This is due to the small contact area between the pieces and loading perpendicular to the grain inside the dovetail pocket.

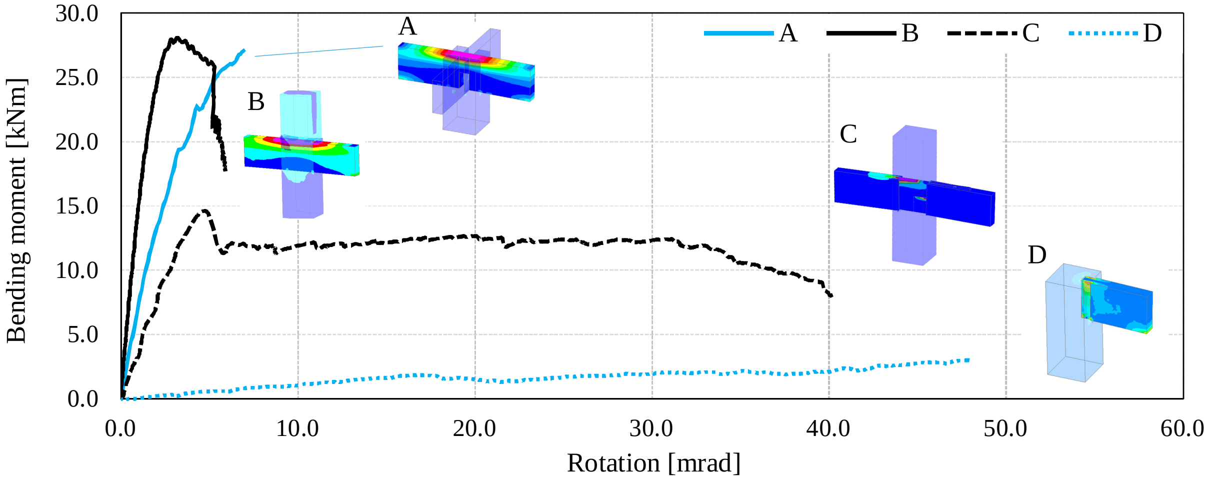

Figure 5. Moment-Rotation behavior of the four selected joints

5. Discussion

This preliminary study allowed for a relative comparison between different joint typologies. It is apparent that the geometry of the cross-section at the joint is a direct correlation to the capacity and stiffness of the member.

Joint C connects two beams to a column and joints A and B consist of a continuous beam running through or over a column. All three joint types could potentially be placed in the case study building at beam-column or beam-beam connections depending on the archetype layout. The selection of the joint depends on the required construction method and the structural demand. The continuous beams in joints A and B allow higher bending moments and result in less rotation. If necessary, two beams can be connected employing joint C while still achieving a certain rigidity. The opening of joint C, as indicated in Figures 5 and 6, is primarily caused by a vertical sliding of the tenon out of the mortise. As e.g. reported in [6], this behavior can be circumvented by additionally inserting a horizontal pin through tenon and mortise. Joint D exhibits a very limited rotational stiffness and can be considered as a hinged connection.

The considered strengths in compression and tension reported in [25] are higher than typical wood design values, yet still permit a relative comparison of joint types. For the structural design of traditional moment-resisting joints in today building construction, the strengths should be reduced to design values.

6. Conclusion and Future Work

This paper investigated traditional Japanese and Chinese interlocking wood connections through state-of-the-art numerical modeling techniques. First, a literature review of the historical context of interlocking wood joints was presented, and past studies of numerical modeling techniques for these joints were reviewed. Then, the structural capacity and load-deformation behavior of the selected joints were compared and contextualized. Future studies should diversify the joint topologies and conduct experimental testing to confirm the results or update the assumptions. Furthermore, modernizing the ancient geometries of the joints may be achieved through optimization techniques (e.g. varying tenon lengths and widths) to increase or customize the rigidity of the connection.

The goal of this preliminary investigation is to initiate a library of interlocking wood joint typologies based on their structural behavior. The comparative record of their capacity and stiffness will allow academics and designers to push the capabilities of these ancient techniques while benefitting from modern materials, construction techniques and fabrication tools.

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